

# The Return of the Phoenix Universe

Jean-Luc Lehnert<sup>\*</sup>

*Princeton Center for Theoretical Science,*

*Princeton University, Princeton, NJ 08544 USA*

Paul J. Steinhardt<sup>†</sup>

*Princeton Center for Theoretical Science and Joseph Henry Laboratories,*

*Princeton University, Princeton, NJ 08544, USA*

Neil Turok<sup>‡</sup>

*Perimeter Institute for Theoretical Physics,*

*Waterloo, Ontario, Canada N2L 2Y5*

(Dated: 30th March 2009)

Georges Lemaitre introduced the term *phoenix universe* to describe an oscillatory cosmology with alternating periods of gravitational collapse and expansion. This model is ruled out observationally because it requires a supercritical mass density and cannot accommodate dark energy. However, a new cyclic theory of the universe has been proposed that evades these problems. In a recent elaboration of this picture, almost the entire universe observed today is fated to become entrapped inside black holes, but a tiny region will emerge from these ashes like a phoenix to form an even larger smooth, flat universe filled with galaxies, stars, planets, and, presumably, life. Survival depends crucially on dark energy and suggests a reason why its density is small and positive today.

*Essay written for the Gravity Research Foundation 2009 Awards for Essays on Gravitation.*

---

<sup>\*</sup>Electronic address: jlehnert@princeton.edu

<sup>†</sup>Electronic address: steinh@princeton.edu

<sup>‡</sup>Electronic address: nturok@perimeterinstitute.ca

*“those solutions where the universe expands and contracts successively [...], have an indisputable poetic charm and make one think of the phoenix of legend.”*

Georges Lemaitre, 1933 [1]

Two breakthroughs of the twentieth century changed forever our understanding of the universe: the observation that the universe is expanding, made in the 1920s, and that the expansion rate is accelerating, made in the 1990s. The full implications have yet to be realized. The currently favored inflationary picture does not explain the origin of the expansion – the big bang – or provide a rationale for the current acceleration. Recently, though, a new cosmological model has emerged that breathes new life into an old idea – the *phoenix universe* – providing an explanation for both the bang and the dark energy, and suggesting why the latter must be small and positive today.

The “phoenix” was first introduced into cosmology by Georges Lemaitre shortly after Hubble’s discovery that the universe is expanding. Friedmann and Lemaitre had discussed the expanding universe model several years earlier, but its realization in nature forced cosmologists to face up to its baffling beginning: the big bang, the moment about fourteen billion years ago when the temperature and density reached infinite values. The standard interpretation today is that the bang marked the beginning of space and time. However, this is far from proven: all we really know is that Einstein’s equations fail and an improved theory of gravity is needed. In fact, the idea of a “beginning,” the emergence of the universe from nothing, is a very radical notion. A more conservative idea is that the universe existed before the big bang, perhaps even eternally. Historically, this motivated many of the founders of the big bang theory, including Friedmann, Lemaitre, Einstein and Gamow, to take seriously an “oscillatory” universe model in which every epoch of expansion is followed by one of contraction and then by a “bounce,” at an event like the big bang, to expansion once more. For the model to work, the matter must exceed the critical density required for its self-attraction to slow the expansion and eventually reverse it to contraction. But by the end of the twentieth century, observations had shown the opposite: the matter density is subcritical and the expansion is speeding up [2].

Yet, today, the phoenix universe has been revived due to the development of a new cyclic theory of the universe that incorporates dark energy and cosmic acceleration in an essential way [3]. To explain the theory, it is useful to invoke a picturesque version inspired by string

theory and M-theory in which space-time consists of two three-dimensional braneworlds separated by a tiny gap along an additional spatial dimension. One of these braneworlds is the world we inhabit. Everything we can touch and see is confined to our braneworld; the other is invisible to us. According to this picture, the big bang corresponds to a collision between the braneworlds, followed by a rebound. Matter, space and time exist before as well as after, and it is the events that occur before each bang that determine the evolution in the subsequent period of expansion.

Unlike Lemaitre's phoenix universe, the matter density is subcritical, consistent with observations. The big bang repeats at regular intervals because a spring-like force keeps drawing the braneworlds together along the extra dimension, causing them to collide every trillion years or so. Associated with the spring-like force are kinetic and potential energy, which play an important role as the source of dark energy in the cyclic model.

The dark energy equation of state  $w$  is defined as the ratio of the pressure (kinetic minus potential energy of the braneworlds) to the total energy density (kinetic plus potential energy). When the braneworlds are farthest apart, the total energy is predominantly potential and positive, corresponding to  $w \approx -1$ , similar to a cosmological constant. Although this potential energy is negligible right after a collision, it decreases slowly and, about nine billion years later, overtakes the matter density, causing the expansion of the braneworld to accelerate. The acceleration cannot last forever, though, because the spring eventually releases, causing the braneworlds to hurtle towards each other. Now, the potential energy decreases and becomes negative while the kinetic energy grows, causing  $w$  to increase sharply from  $w \approx -1$  to  $w \gg 1$  and initiating a period known as "ekpyrosis" [4]. From the point of view of a "braneless observer," someone who is unaware of the extra dimension and the other braneworld and reinterprets the goings-on in terms of usual Einstein general relativity, the universe appears to be undergoing a peculiar period of ultra-slow contraction in which the scale factor  $a(t) \sim (t_{bang} - t)^{2/3(1+w)}$  as  $t$  approaches  $t_{bang}$  with  $w \gg 1$ . The dark energy continues to dominate the universe during this ekpyrotic contraction phase, and the matter density remains negligibly small.

The ekpyrotic phase is key, because it removes any need for inflation. The horizon problem is resolved simply because the universe exists long before the big bang, allowing distant regions to become causally connected. To see how the flatness puzzle is solved without inflation, recall that the problem arises in a slowly expanding universe, where a

small deviation from flatness at early times grows into an unacceptably large one by the present epoch. But now just run the story backwards: as space slowly contracts, an initially large deviation from flatness shrinks to an infinitesimal one. In an ekpyrotic contraction phase, because  $w \gg 1$ , the deviation from flatness is diminished by more than it grows during the subsequent expansion phase, thus explaining why it is negligibly small today [5].

Both ekpyrotic contraction and inflation can generate large scale density fluctuations from microscopic quantum fluctuations. In inflation this occurs because quantum fluctuations are stretched exponentially while the Hubble horizon increases very slowly, so the fluctuations end up spanning superhorizon scales. In the ekpyrotic contraction phase, the same feat is accomplished because the quantum fluctuations remain nearly fixed in scale while the Hubble horizon shrinks rapidly. By the time the phase ends, quantum fluctuations formed inside the horizon span superhorizon scales, resulting in a spectrum of nearly scale-invariant fluctuations very similar to inflation, although with observably different predictions for primordial gravitational waves [6] and non-Gaussian density fluctuations [7].

An important caveat arises, though, for the best understood example of ekpyrosis, where the density perturbations are generated by a so-called entropic mechanism [8]. The ekpyrotic energy only maintains  $w \gg 1$  if the quantum fluctuations remain within a narrow range. Otherwise,  $w$  drops precipitously, inhomogeneities and curvature grow, and space collapses into a warped amalgamation of black holes. The chance of avoiding decimation is small: during every e-fold of contraction, quantum fluctuations reduce the fraction of space with  $w \gg 1$  by  $1/e$ . Since the ekpyrotic phase lasts for about 120 e-folds, the fractional volume of space that makes it smoothly to the bounce and re-emerges in a flat, expanding phase is  $f \approx e^{-360}$  [9]. This fraction is so tiny that, if the ekpyrotic phase started today, fourteen billion years after the big bang, the entire observable universe ( $10^{84} \text{ cm}^3$  across) would be decimated.

Dark energy saves the universe from this ashen fate by causing the expansion to accelerate. If acceleration continues for at least 560 billion years ( $> 56$  e-folds), a volume of at least a cubic centimeter will retain its  $w \gg 1$  ekpyrotic form all the way to the next crunch and emerge unscathed: flat, smooth and isotropic. As tiny as a cubic centimeter may seem, it is enough to produce a flat, smooth region a cycle from now at least as large as the region we currently observe. In this way, dark energy, the big crunch and the big bang all work together so that the phoenix forever arises from the ashes, crunch after crunch after crunch.

The revival of the phoenix universe could also resuscitate an old proposal for solving one of the deepest mysteries in science: why the cosmological constant (or, equivalently, the dark energy density when  $w \approx -1$ ) is  $10^{120}$  times smaller than dimensional analysis suggests. The proposal involved introducing a mechanism which causes the cosmological constant to relax to smaller values. Starting out large, it naturally decreases but its downward drift slows dramatically as it becomes small. Should it ever slip below zero, gravitational collapse follows swiftly. The result is that, for a vast majority of the time and throughout almost all of space, the cosmological constant is tiny and positive, just as we observe.

Attempts to incorporate this idea into models where the big bang is the beginning failed because the relaxation process takes vastly longer than fourteen billion years. There is plenty of time in a cyclic universe, though. The relaxation can occur without disrupting the cycles and vice-versa, so that an overwhelming majority of cycles occur when the cosmological constant is small and positive [10]. By incorporating the effects of dark matter, ordinary matter and radiation on the rate of drift, it may even be possible to explain the quantitative value observed today.

- 
- [1] G. Lemaitre, *Annales Soc. Sci. Brux. Ser. I A* **53**, 51 (1933).
  - [2] E. Komatsu *et al.* [WMAP Collaboration], *Astrophys. J. Suppl.* **180**, 330 (2009).
  - [3] P. J. Steinhardt and N. Turok, *Science* **296**, 1436 (2002); *Phys. Rev. D* **65**, 126003 (2002).
  - [4] J. Khoury, B. A. Ovrut, P. J. Steinhardt and N. Turok, *Phys. Rev. D* **64**, 123522 (2001).
  - [5] To complete the argument, note that, as shown in J. K. Erickson, D. H. Wesley, P. J. Steinhardt and N. Turok, *Phys. Rev. D* **69**, 063514 (2004), not only curvature, but also anisotropies are suppressed in a contracting phase with  $w > 1$ .
  - [6] L. A. Boyle, P. J. Steinhardt and N. Turok, *Phys. Rev. D* **69**, 127302 (2004).
  - [7] J. L. Lehnert and P. J. Steinhardt, *Phys. Rev. D* **77**, 063533 (2008) [Erratum-ibid. *D* **79**, 129903 (2009)]; *Phys. Rev. D* **78**, 023506 (2008) [Erratum-ibid. *D* **79**, 129902 (2009)]; arXiv:0909.2558 [hep-th]; J. L. Lehnert and S. Renaux-Petel, *Phys. Rev. D* **80**, 063503 (2009).
  - [8] J. L. Lehnert, P. McFadden, N. Turok and P. J. Steinhardt, *Phys. Rev. D* **76**, 103501 (2007).
  - [9] J. L. Lehnert and P. J. Steinhardt, *Phys. Rev. D* **79**, 063503 (2009).
  - [10] P. J. Steinhardt and N. Turok, *Science* **312**, 1180 (2006).